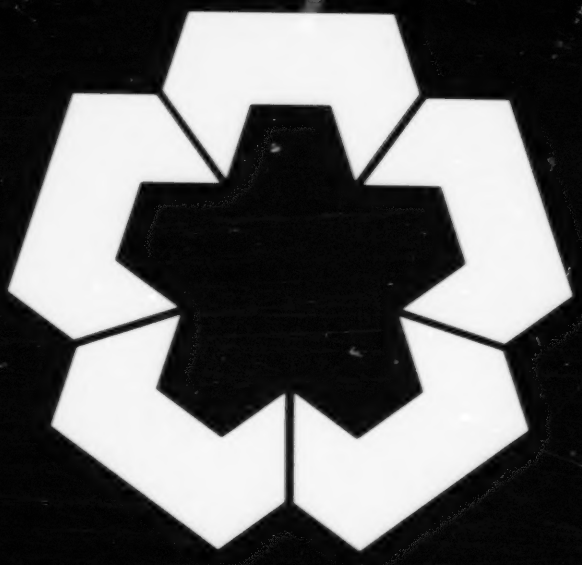

Injection of Silver Iodide From Cloud Seeding Into the Atmosphere Of Central Alberta

RMD Report 83/20

Alberta

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INJECTION OF SILVER IODIDE FROM CLOUD SEEDING INTO THE ATMOSPHERE OF CENTRAL ALBERTA

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For further information on reports published by the Research Management Division, contact:

Research Management Division
14th Floor, Standard Life Centre
10405 - Jasper Avenue
Edmonton, Alberta
T5J 3N4

(403) 427-3946

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INJECTION OF SILVER IODIDE FROM CLOUD SEEDING INTO THE ATMOSPHERE OF CENTRAL ALBERTA

by

J.M.L. GRAY
G.G. GOYER

Alberta Research Council

for

RESEARCH MANAGEMENT DIVISION
Alberta Environment

RMD 83/20

April 1983

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ABSTRACT

A total of 8590 kg of silver iodide was used for cloud seeding in the Province of Alberta between 1956 and 1981. Of this total, about 5200 kg were used in the Alberta Hail Project area in central Alberta between 1968 and 1981. The annual total release averaged 13 g km^{-2} over the whole project area, with values ranging from a low of 2.4 g km^{-2} in the NW quadrant during 1975 to a high of 29.2 g km^{-2} in the NW quadrant during 1979.

The environmental impact from this level of cloud seeding is probably insignificant because of the low solubility of silver iodide and the potentially large sources of other silver species.

ACKNOWLEDGEMENTS

The authors thank Mr. E.V. Zacharuk and Mr. R.J. Deibert for their help in collecting the data on silver iodide releases in the Alberta Hail Project area; Dr. M.A. Kessick and Dr. B.L. Barge for reviewing the report; and Miss M. Tatchyn for help in typing the report. Special thanks are due to Mrs. B. Turner for her efforts in the preparation of this report. Financial support from the Research Management Division, Alberta Environment, is gratefully acknowledged.

1. INTRODUCTION

Cloud seeding with silver iodide has been conducted in Alberta since 1955. Because of the potential toxicity of silver in the environment, the Alberta Research Council was contracted to evaluate the amounts of silver released and to review the literature on possible impacts. The objectives of the study were:

1. To review the literature related to the deleterious effects of silver iodide.
2. To determine the total mass of silver iodide released from cloud-seeding activities between 1955 and 1981.
3. To determine the total area where silver iodide was released.
4. To estimate the average mass of silver iodide released per square kilometer in various segments of the Alberta Hail Project area.
5. To discuss the possible ecological effects of silver iodide in the Alberta Hail Project area.
6. To provide recommendations on future action.

2. SILVER FROM CLOUD SEEDING IN ALBERTA

2.1 HISTORY OF CLOUD SEEDING IN ALBERTA

The hailstorm and its modification have been the subject of intense investigation in Alberta for many decades because the annual crop losses from hailstorms can exceed one hundred million dollars. Following a number of heavy hail loss years in the early 1950s, independent research and operational hail suppression programs were initiated in Central Alberta. Figure 1 shows the experimental areas where cloud seeding was conducted between 1956 and 1981.

An operational hail suppression program, organized and funded by area farmers who formed the Alberta Weather Modification Cooperative (AWMC), operated from 1956 to 1968. The area and the shape of the operational cloud-seeding zone varied greatly over the years from an area of 1400 km^2 to a maximum area of 11 655 km^2; however, the experimental area in which hail modification experiments were conducted in all thirteen years of the AWMC program was basically the L-shaped area of 4532 km^2 identified as "AWMC Seed Area" on Figure 1. Although up to 190 silver iodide ground-level seeding generators were used at various times during the thirteen years of the program, only a limited number were used on any given day. From 1957 to 1968, airborne seeding was conducted in addition to the ground-based seeding procedures. The annual mass of silver iodide dispersed into the atmosphere by the AWMC hail suppression program varied from 50 kg in 1956 to 266 kg in 1968. No ground-based cloud seeding was conducted in 1969.

Research on convective storms in general, with an emphasis on hailstorms, was also initiated in Alberta in 1956. With support from the National Research Council, the Canadian Meteorological Service, and the Alberta Government, the Alberta Research Council (ARC) and McGill University participated in a co-operative research program known as the Alberta Hail Studies project (ALHAS). After a decade of convective storm research, ALHAS began studies of cloud seeding in 1969.

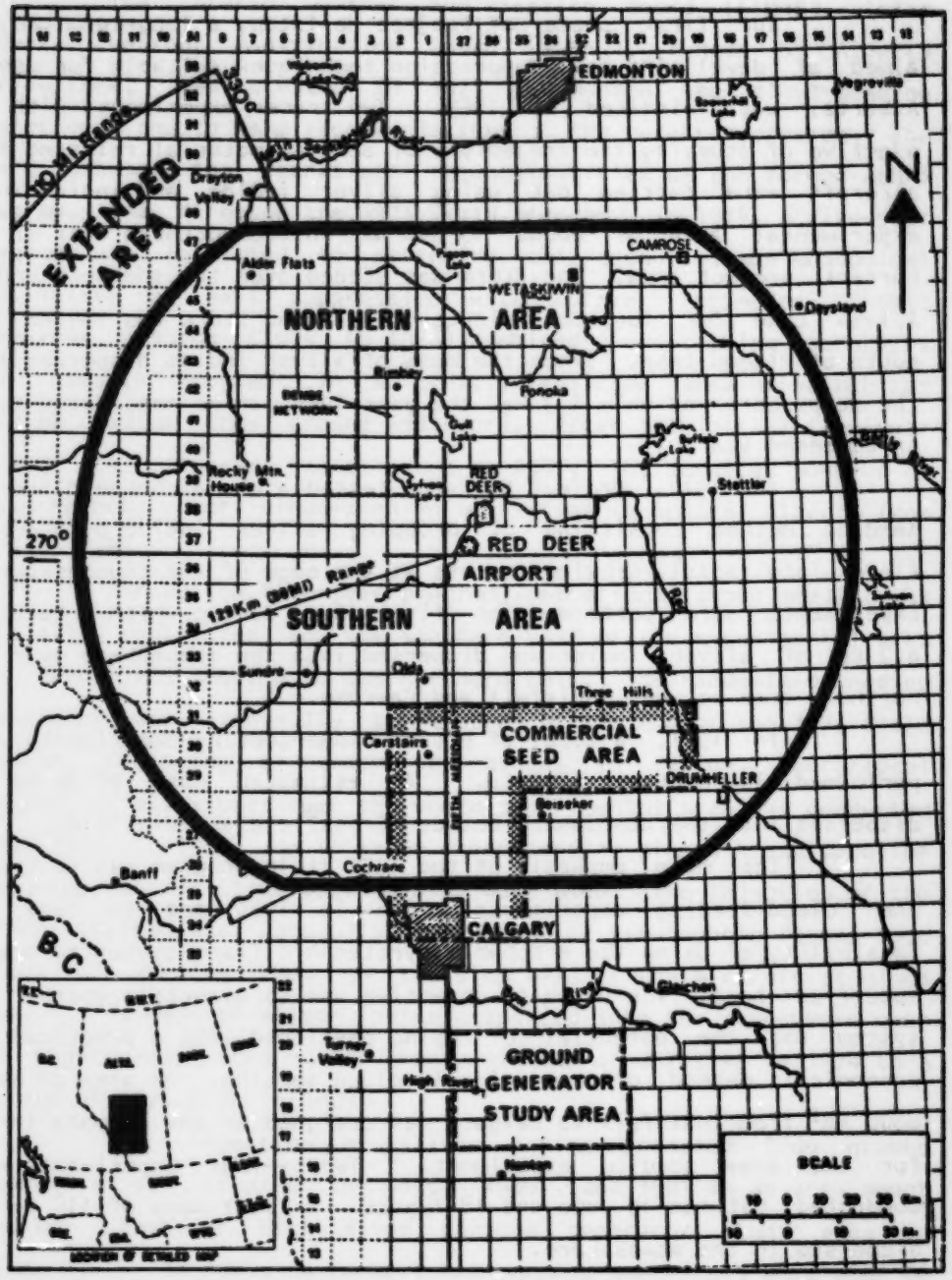

Figure 1. Cloud-seeding areas in Alberta.

The first phase of Project Hailstop, a long-term project aimed at developing hail suppression techniques suitable for use in Alberta, was initiated in 1969. Two tracer experiments with the ojective of studying the trajectory of seeding material released from aircraft were carried out using silver iodide and indium in an experimental area of about 18 648 km^2 in the northern half of the current project area. One storm was seeded over the southern end of Sylvan Lake for fourteen minutes. A second storm was seeded just south of Pigeon Lake. Since the mass of silver iodide dispersed into the atmosphere was only 1.3 kg, the year 1969 can be considered to be an unseeded year.

In 1970, Project Hailstop tested a new airborne cloud-top seeding method consisting of dropping silver iodide pyrotechnic flares into rapidly-growing turrets at the edge of the thunderstorms. Experiments were performed on five days during which a total of 4.2 kg of silver iodide was dispersed into the atmosphere over the northern area between Innisfail and Camrose.

In 1971, a total of eleven cloud-seeding experiments were performed in central Alberta. An estimated mass of 25 kg was dispersed into the atmosphere between Crossfield and Winfield.

The main emphasis of the 1972 field program was to expand the cloud-seeding experiments begun in 1970 and to test the feasibility of using the droppable pyrotechnic flare system to seed a specified area. The ultimate objective was to ascertain whether the system had the potential of being developed into a practical and economical method of operational cloud seeding. An area of about 8800 km^2 from Innisfail to Calgary was assigned as the primary target for the area seeding experiment. Twenty-four experiments were conducted between 19 June and 18 August. A total mass of 118 kg was dispersed in the atmosphere.

In 1973, 3900 km^2 were added to the eastern edge of the previous primary seeding target area, bringing the seeding experimental area to about 13 000 km^2. Eleven experiments were performed between 20 June and 10 September. Thirteen hundred and thirty six flares were used, dispersing 69 kg of silver iodide.

The Interim Weather Modification Board ([IWMB], later Alberta Weather Modification Board [AWMB]), funded by Alberta Agriculture, was created in 1973 to manage the cloud-seeding operations and to make recommendations on the research program. The Board assumed the operational responsibilities of the former ALHAS program, and directed the 1973 field program. In 1974, a five-year program was initiated to determine the technical and economical feasibility of hail suppression with current technology. This five-year program (1974 to 1978) combined cloud-seeding operations and research programs in a greatly enlarged area of 48 000 km^2 (120 km radius area around Red Deer). After the initial five-year period, the program was extended to 1981. The detailed portion of this report covers cloud-seeding activities in central Alberta from 1974 to 1981.

During the five-year program, operational cloud seeding was initially restricted to the southern half of the experimental area and randomized seeding to the northern half. The randomized seeding experiment was eventually terminated at the end of the 1976 field program, following a number of changes in design. Operational seeding of all storms over the whole experimental area was conducted from 1977 to 1981. Up to seven cloud-seeding aircraft equipped for cloud-top and/or cloud-base seeding were used. The injection of the silver iodide was accomplished by dropping pyrotechnic flares into clouds or burning them on the wing tips of the aircraft at cloud base. The mass of silver iodide dispersed into the atmosphere over the experimental area varied from a minimum of 257.3 kg in 1974 to a maximum of 1075.8 kg in 1979.

The injection of silver iodide produced from ground generators was studied in 1975, 1980, and 1981 in an area about 2000 km^2 east of High River (ground generator study area on Figure 1). In 1975, up to seventeen ground generators were used on 35 days, dispersing a total mass of 32 kg of silver iodide. In 1980 and 1981, 38.4 kg and 60.8 kg respectively were injected into the atmosphere by a network of ground generators in approximately the same area as that used in 1975. Figures 2 and 3 show the ground

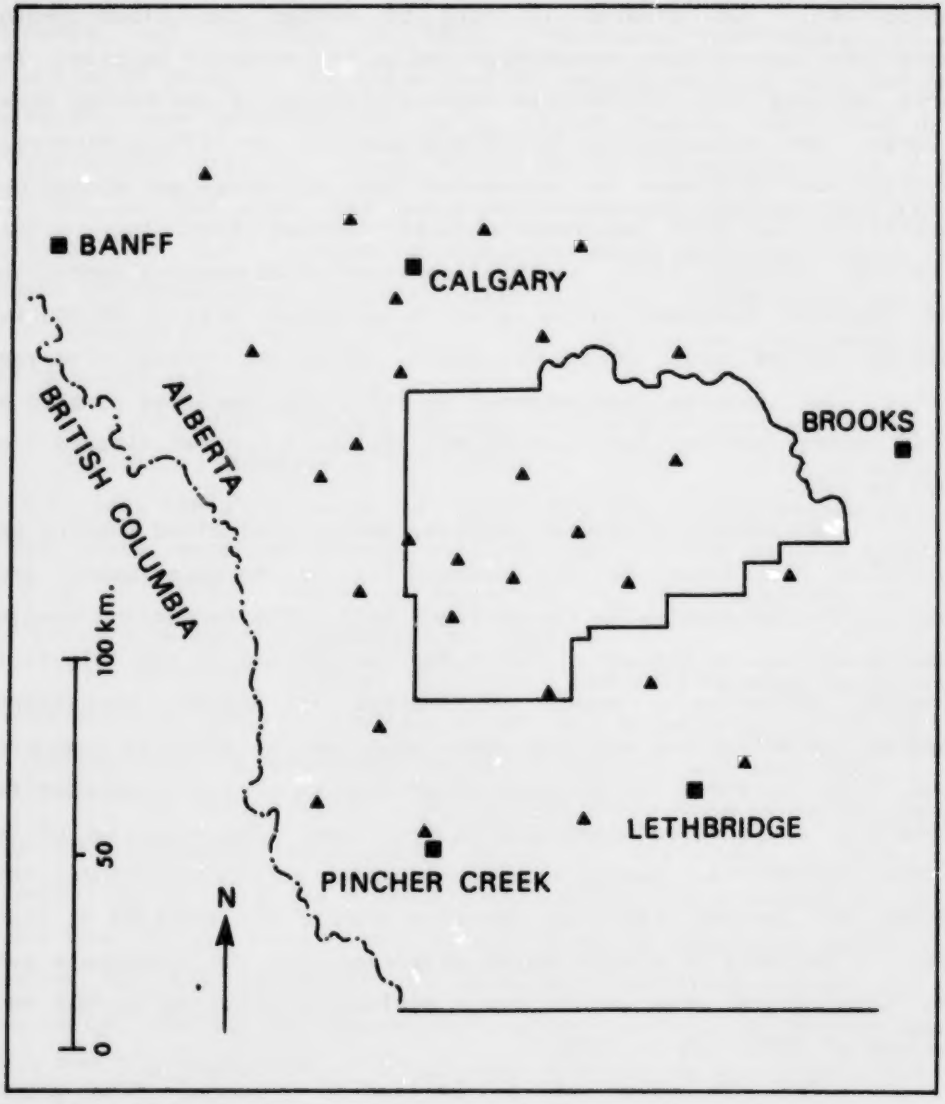

Figure 2. 1980 ground generator network.

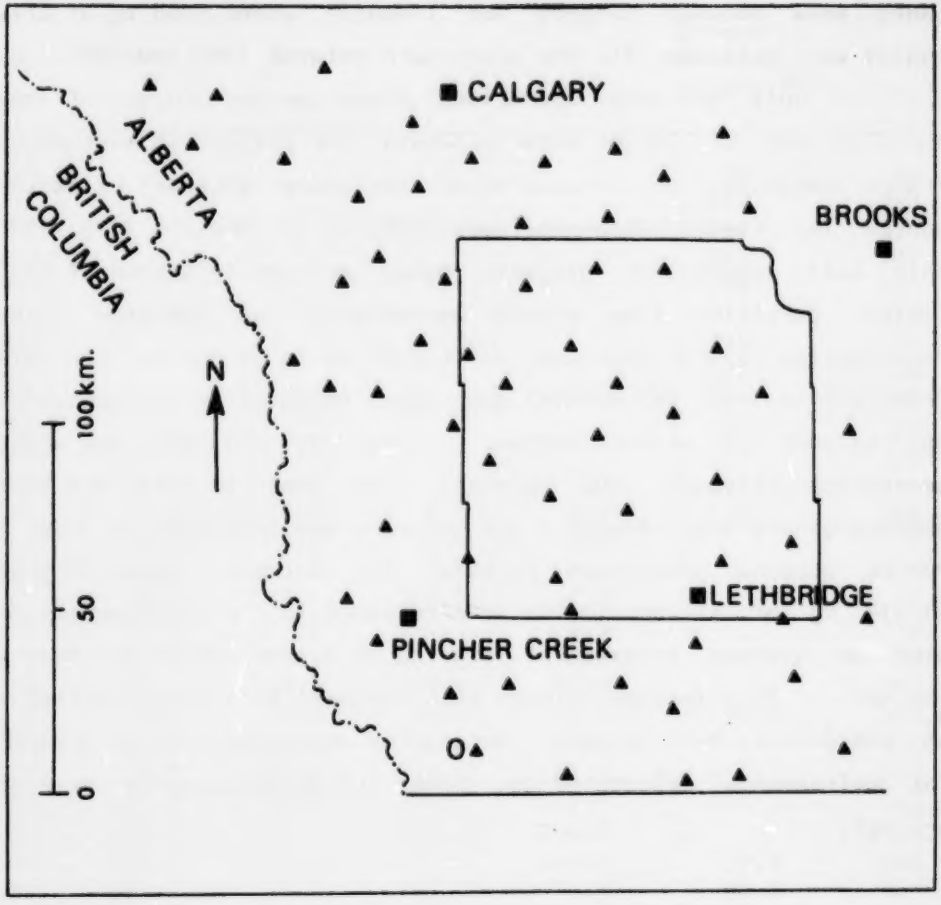

Figure 3. 1981 ground generator network.

generator network for 1980 and 1981. The mass of silver iodide released by the ground generators is not included in the detailed portion of this report which is confined to the Alberta Hail Project (AHP) area between Calgary and Edmonton where 5188 kg of silver iodide were released into the atmosphere between 1968 and 1981.

Only one other operational cloud-seeding project of longer duration and of larger area is known: the project in southwestern France conducted by l'Association Nationale d'Etude et de Lutte contre les Fleaux Atmospheriques (ANELFA) (J. Dessens 1979, 1980). This hail suppression project, based on the injection of silver iodide particles from ground generators, has operated without interruption since 1952 over an area of up to 94 500 km^2 (in 1979). From 1952 to 1958, 84 charcoal generators released an average mass of 352 kg/year of silver iodide. From 1959 to 1962, 125 acetone generators released 1000 kg/year; from 1963 to 1973, 412 vortex acetone generators released 3 572 kg/year; and from 1974 to 1979, 500 vortex acetone generators released 863 kg/year. Over 28 years, 50 934 kg of silver iodide were released in the experimental area with an average release of 1.9 kg of silver iodide per year per 100 km^2. This average release rate compares to 1.3 kg/year/100 km^2 in the Alberta Hail Project. No studies were conducted to determine the environmental effects of the silver iodide released by the French project.

2.2 SILVER IODIDE RELEASES IN THE ALBERTA HAIL PROJECT AREA

A summary of the silver iodide released in Alberta from cloud seeding activities is given in Table 1. The monthly releases by quadrant, the annual totals, and the average areal distribution (AAD) have been calculated for the Alberta Hail Project area during the years 1974 to 1981 using the fifth meridian and the dividing line between townships 36 and 37 as boundaries (Table 2). The average areal distribution was calculated assuming that all of the silver iodide released in an area was eventually deposited on the ground in that area. Although this is simplistic, any more rigorous calculation would require other simplifying assumptions and

Table 1. Summary of silver iodide released for cloud seeding, 1956–1981 (kg AgI).

Year	SW	SE	NW	NE	Ground Generator Studies[a,b]	Total
1956					50	50
1957					258	258
1958					250	250
1959					291	291
1960					399	399
1961					177	177
1962					134	134
1963					328	328
1964					236	236
1965					352	352
1966					333	333
1967					196	196
1968	0.2	0.0	0.2	0.0	266	266
1969	0.2	0.5	0.6	0.0		1.3
1970	0.9	1.0	2.3	0.0		4.2
1971	6.1	5.1	6.8	7.0		25.0
1972	81.7	17.4	15.8	3.4		118.3
1973	54.9	2.3	11.5	0.3		69.0
1974	109.7	68.0	48.5	31.1		257.3
1975	134.1	36.1	29.4	49.7	32.3	281.6
1976	159.2	165.5	80.6	69.7		475.0
1977	223.7	170.7	237.3	186.1		817.8
1978	291.2	98.1	210.5	203.7		803.5
1979	308.0	177.7	350.3	239.8		1075.8
1980	248.6	149.5	264.8	207.4	38.4	908.7
1981	163.8	55.8	128.3	72.9	60.8	481.6
Total	1782.3	947.7	1386.9	1071.1	3401.5	8589.5

Total 5188 kg

[a] Source: Peterson (1971).

[b] Data from 1956 to 1968 includes airborne seeding as well as ground based.

Table 2. Distribution of silver iodide in the Alberta Hail Project, 1974–1981 (grams AgI).

1974

MONTH	SW	SE	NW	NE
JUNE	47 160	28 100	17 470	5 750
JULY	40 990	19 210	27 580	24 070
AUGUST	21 530	18 790	3 430	1 190
SEPTEMBER	0	1 890	0	70
TOTAL	109 680	67 990	48 480	31 080
AAD[a] (g km^{-2})	9.1	5.7	4.0	2.6

1975

MONTH	SW	SE	NW	NE
JUNE	43 190	16 160	4 630	3 300
JULY	57 080	9 620	10 360	22 280
AUGUST	30 470	9 550	12 760	21 980
SEPTEMBER	3 360	770	1 600	2 100
TOTAL	134 100	36 100	29 350	49 660
AAD (g km^{-2})	11.2	3.0	2.4	4.1

1976

MONTH	SW	SE	NW	NE
JUNE	2 800	4 690	5 320	2 380
JULY	74 790	36 000	54 530	25 480
AUGUST	80 140	124 830	20 730	41 840
SEPTEMBER	1 450	0	0	0
TOTAL	159 180	165 520	80 580	69 700
AAD (g km^{-2})	13.3	13.8	6.7	5.8

1977

MONTH	SW	SE	NW	NE
JUNE	44 180	24 990	9 860	11 300
JULY	135 955	70 300	137 915	74 080
AUGUST	29 690	50 645	57 295	87 670
SEPTEMBER	13 890	24 785	32 265	13 065
TOTAL	223 715	170 720	237 335	186 115
AAD (g km^{-2})	18.6	14.2	19.8	15.5

continued . . .

Table 2. Concluded.

1978

MONTH	SW	SE	NW	NE
JUNE	76 890	34 720	39 965	40 720
JULY	160 945	50 910	118 830	126 400
AUGUST	53 405	6 900	51 450	27 750
SEPTEMBER	0	5 595	300	8 835
TOTAL	291 240	98 125	210 545	203 750
AAD (g km^{-2})	24.3	8.2	17.5	17.0

1979

MONTH	SW	SE	NW	NE
JUNE	19 000	15 420	45 920	42 415
JULY	131 110	102 140	207 095	116 540
AUGUST	119 620	26 150	63 925	58 685
SEPTEMBER	38 270	33 975	33 355	22 200
TOTAL	308 000	177 685	350 295	239 840
AAD (g km^{-2})	25.7	14.8	29.2	20.0

1980

MONTH	SW	SE	NW	NE
JUNE	53 950	21 600	16 700	5 850
JULY	125 750	99 750	16 700	132 050
AUGUST	61 850	25 900	168 550	69 500
SEPTEMBER	7 030	2 250	79 500	0
TOTAL	248 580	149 500	264 750	207 400
AAD (g km^{-2})	20.7	12.5	22.1	17.3

1981

MONTH	SW	SE	NW	NE
JUNE	18 523	2 808	19 012	12 447
JULY	82 301	11 722	89 659	33 324
AUGUST	63 033	41 234	19 616	27 158
TOTAL	163 857	55 764	128 287	72 929
AAD (g km^{-2})	13.7	4.6	10.7	6.1

[a] AAD = average areal distribution.

additional supporting data. The results show that cloud-seeding activity reached a peak in 1979 with an average areal distribution of 22.4 g km^{-2} and a maximum areal distribution of 29.2 g km^{-2} in the northwest quadrant. A summary of the total releases of silver iodide in the Alberta Hail Project area during the years 1974 to 1981 is given in Table 3. The average annual areal distribution of 13 g km^{-2} in the Alberta Hail Project is of the same magnitude as that of the French project (19 g km^{-2}).

The most extensive and intensive cloud-seeding program conducted in Alberta was the Alberta Hail Project. The total average areal distribution of silver iodide released during this project is the equivalent of one to two flares released per square kilometer over the whole project area. The contribution of the silver from cloud seeding agents to the total soil silver would therefore be minimal.

2.3 SILVER IN PRECIPITATION AND THE ATMOSPHERE

The results from an ARC study of silver concentrations in precipitation are shown in Tables 4 and 5. Although the concentrations of silver in precipitation during seeding periods are higher than the background concentrations, the average silver levels are still one to three orders of magnitude below the recommended limits cited in Guidelines for Canadian Drinking Water Quality 1978 (maximum acceptable = 50 µg L^{-1}, objective = 5 µg L^{-1}). Background concentrations of silver found in precipitation at other locations in North America ranged from 4 ng L^{-1} to 100 ng L^{-1} (Mulvey 1978).

No measurements of silver in atmospheric particulates have been made in Alberta. Shewchuk (1979) measured the "excess" silver concentration in atmospheric particulates at several sites in Saskatchewan during 1978 and attributed this excess to cloud-seeding activities in Alberta (Table 6). The background concentration of silver in atmospheric particulates is estimated at less than 0.1 ng m^{-3} (Mulvey 1978). Ambient air concentrations found at locations near anthropogenic sources have ranged from 0.17 to 7 ng m^{-3} (Smith and Carson 1977). Douglas 1968 (cited by Smith and

Carson 1977) reported a maximum of 1 ng m^{-3} in a cloud-seeded target area.

Table 3. Summary of silver iodide distribution, Alberta Hail Project, 1974-1981.

	SW	SE	NW	NE	Total
AgI (kg)	1638	923	1349	1061	4971
Average Areal Distribution ($g\ km^{-2}$)	136.5	76.9	112.4	88.4	103.6

Table 4. Silver in precipitation: 1975 background study samples.[a]

Silver[b] Concentration ng L^{-1}	No. of Samples	Silver Concentration ng L^{-1}	No. of Samples
2[c]	341	12	0
3	18	13	1
4	13	14	1
5	7	15	0
6	3	16	1
7	4	17	0
8	0	18	0
9	0	19	0
10	0	20	1
11	1		

Calculated Mean = 2.2 ng L^{-1}

[a] Source: Zacharuk, Erb, and Goyer 1979.

[b] Samples showing visual dirt contamination were discarded and not taken into account.

[c] Values of ≤ 2 are considered as 2 ng L^{-1}.

Table 5. Silver in precipitation, 1974-1976.[a]

Mixed Rail and Hail	1974	1975	1976		Three Year Mean
No. with Ag	86	73	63		74
Total No.	383	424	244		1051
Max. Ag conc (ng L^{-1})	107	340	530		326
Mean Ag conc (ng L^{-1})	8	5	28		14
Rain Samples			**Seed**	**No-Seed**	
No. with Ag	289	231	347	40	289
Total No.	912	967	969	450	3298
Max. Ag conc (ng L^{-1})	414	358	510	99	427
Mean Ag conc (ng L^{-1})	12	12	16	4	13

[a] Source: Zacharuk, Erb, and Goyer 1979.

Table 6. Maximum excess concentration of silver in the aerosols of Saskatchewan during the weekly sampling periods of 1978.[a]

Location	Period	Concentration (ng/m^{-3})
Alsask	September 1 to 8	0.36
Lloydminster	August 11 to 18	0.48
Saskatoon		0.0[b]
Swift Current		0.0[b]
Estevan	September 1 to 8	0.35

[a] Source: Shewchuk 1979.

[b] Below the minimum detectable amount of 0.10 ng/m^{-3}.

3. SILVER IN THE ENVIRONMENT: CONCENTRATIONS AND EFFECTS

3.1 INTRODUCTION

The geochemistry, sources, effects, and distribution of silver in the environment have been extensively studied. Boyle (1968) reviewed the geochemical knowledge of silver and its abundance in various natural materials. Patterson (1963) summarized production statistics and the distribution of silver mining and refining operations in Canada. Cooper and Jolly (1970) summarized the known effects of silver iodide seeding agents and the direct effects of silver iodide relative to general ecological impacts of weather modification (Cooper and Jolly 1969). Howell (1977) presented an overview of the general ecological impact of intentional precipitation management practices, including the direct effects of seeding agents. The most definitive works, however, are those of Smith and Carson (1977) and Klein (1978a). Smith and Carson have compiled a comprehensive review of silver in the environment: distribution, sources, economics, recovery processes, uses, losses to the environment, physiological effects, human health hazard, and data on silver compounds. Klein has edited a definitive monograph on the environmental impact of artificial ice nucleating agents. This book thoroughly summarizes the current knowledge of the environmental impact of seeding agents.

Because the literature has been so excellently and comprehensively reviewed by other authors, we will make no attempt to review the literature in detail, but will attempt to summarize the relevant findings.

The iodine portion of silver iodide is generally considered to be harmless (Cooper and Jolly 1970) since the iodine concentrations resulting from cloud seeding are negligible compared with other environmental sources of iodine. Ionic silver, however, is considered toxic by official sources, as evidenced by the maximum acceptable concentrations assigned to silver in water (Guidelines for Canadian Drinking Water Quality 1978). Most studies of the toxicity of silver compounds have used easily-ionized species such as silver

nitrate, rather than relatively insoluble species such as the silver halides. The results are, therefore, not applicable to the assessment of silver iodide toxicity. Since a prime requirement of an effective ice-nucleating agent is water insolubility, the assessment of potential environmental impact of silver iodide seeding agents cannot be based on ionic silver data.

3.2 BIOCHEMICAL EFFECTS OF SILVER

Klein (1978b) reviewed the information available on the biochemical effects of silver. His conclusions are summarized as follows:

1. Toxic metal interactions are dependent upon pH, temperature, form of silver, and the ability of living cells to deactivate silver.
2. Silver may react with both sulphydryl-containing enzymes and those without sulphydryl groups to affect membrane permeability.
3. Low levels of silver (10^{-5} M) can increase cell respiration. Toxic effects occur at concentrations above 10^{-4} M.
4. Because of the low concentrations of silver ions generally present in natural environments, the effects of silver ions are difficult to detect. Both stimulatory and inhibitory interactions may occur. The low concentrations of silver are due to complexation of silver by other chemical species and the presence of absorptive organic materials or clays.

3.3 EFFECTS OF SILVER IN SOILS AND SOIL MICROBIOLOGICAL PROCESSES

Boyle (1968) estimates the average terrestrial abundance of silver in the upper lithosphere at 0.10 ppm. The silver content in normal Canadian soils ranges from 0.01 to 5 ppm. The average silver content excluding soils over mineralized zones is 0.3 ppm.

Lindsay and Sadiq (1978) have extensively reviewed the present knowledge of silver equilibria and speciation in soils. They calculate that the silver oxides, sulphates, carbonates and phosphates are too soluble to persist in soils and that the compounds most likely to form, depending on halide ion activity, are the silver iodides, bromides and chlorides. In some reducing environments, the formation of metallic silver and silver sulphide is also possible. They conclude that, considering the high levels of halides which normally exist in typical soils, only a minor fraction of the total silver in soils would occur in the biologically active ionic form. Klein (1978d) reviewed the literature on effects of silver species on soil microbiological processes. He concludes that the silver concentrates in the surface soil zones through both biotic and abiotic processes and subsequent rainfall do not cause major movement below the surface zones. Silver concentrations in soils with high humic contents, such as bog soils and marshes, are relatively high due to silver ion adsorption or complexation with the organic matter. Silver ion can also bind with clay minerals, usually substituting for sodium or potassium. While silver ion absorption is influenced by soil organic matter, silver iodide absorption is largely independent of soil organics (Cameron 1973, cited by Klein 1978d). Once absorbed, the silver is not readily released back into solution. Teller et al. (1976, cited by Klein 1978d) confirmed that most of the silver iodide released from a ground level seeding generator was retained in the top 10 to 15 cm of soil. Only in the immediate vicinity of the generator did the silver penetrate to lower levels.

Although silver ion causes decreased microbial activity, Klein states that, under short-term laboratory conditions, it was difficult to observe any effects with silver iodide. In short-term laboratory studies of effects on soil respiration processes, distinct differences were noted between silver ion and silver iodide. Silver ion showed clear effects at 10 to 100 µg/g levels, while silver iodide showed no effects at 1000 µg/g (Weaver 1972; Klein and Sokol 1976; cited by Klein 1978d). In field conditions, Sokol and Klein

(1975, cited in Klein 1978d) found that silver iodide could have more distinct long-term effects on soil microbiological processes than silver ion, and that increased silver in surface soils might lead to increased microbiological activity rather than decreased activity. The silver levels where effects were first observed were 100-fold higher than levels which normally occur in surface soil zones.

3.4 EFFECTS OF SILVER IN AQUATIC ENVIRONMENTS

Boyle (1968) reports an average silver concentration in fresh waters of 0.2 ppb, with wide regional variations from the average. Acid waters tend to contain more silver than neutral or alkaline waters. Smith and Carson (1977) tabulate the silver concentrations in various city water supplies in the United States. The concentrations vary from 0.3 to 5 ppb, with the average levels commonly less than 0.5 ppb. The average silver concentration reported for seawater is 0.3 ppb. The recommended limit for silver in Canadian drinking water is 50 ppb, with an objective of 5 ppb (Guidelines for Canadian Drinking Water Quality 1978).

Jenne et al. (1978) used analytical and thermodynamic data and a comprehensive chemical model to investigate the inorganic speciation of silver in natural waters. They concluded that the dominant chemical species in most natural waters were $AgCl_2^-$, $AgCl_3^{-2}$, and AgHS.

The interactions, cycles, and fate of silver in aquatic environments has been of concern for many years because of the possibility of concentration in organisms or inorganic material, and because aquatic organisms may come in more direct contact with silver species. For these reasons, several general assessments of potential environmental impact of silver (Smith and Carson 1977; Cooper and Jolly 1969, 1970) have suggested that any environmental impact would probably be observed first in an aquatic environment. Klein (1978f) discussed the potential impact of silver on aquatic systems. His major conclusions are listed below:

1. Most silver entering an aquatic system is complexed by organic matter in sediments and removed from the system.
2. Both adsorption and desorption of silver by river sediment increases at higher pH values, with adsorption being a considerably faster process than desorption.
3. Sediments from a wide range of aquatic systems typically contain 10 to 20 times more silver than their associated waters.
4. In water containing silver concentrations above the drinking water standard (50 ppb), plant and animal life has not been adversely affected, probably because silver is present in biologically inactive forms.
5. Numerous plants and primary consumer organisms accumulate silver. Some organisms can accommodate or become tolerant to increased silver concentrations.
6. There is no strong evidence for silver bioaccumulation in higher trophic levels of ecosystems, even when secondary consumers and predators feed on primary consumers which have accumulated silver.
7. Most information on the toxicological effects of silver has been based on silver ion. The results may not be relevant to assessing the impact of silver iodide.

3.5 EFFECTS OF SILVER ON MICROORGANISMS

Silver is considered toxic to bacteria and has been used as an antimicrobial agent and for water purification. Water contaminated with 200 to 1900 microbiological units of microorganisms has been sterilized using 100 to 200 ppb of silver ion in approximately 20 minutes. Silver ion can also function as an algicide if chlorine, bromine, and iodine are not present (Smith and Carson 1977). This known toxicity of silver ion has been cited as evidence of the toxicity of silver iodide seeding agents, although any direct effects of silver iodide at relevant environmental concentrations is difficult to demonstrate (Klein 1978c).

Klein (1978c) reviewed the literature on the toxicological effects of silver species on microorganisms. Some of his conclusions are presented below:

1. Bacterial and fungal spores are more resistant to silver ion than the actively growing bacteria or fungi. Low silver levels can stimulate microbial activity.
2. Some microorganisms can develop tolerance to silver ion.
3. Some antimicrobial effects have been observed with silver iodide complexes produced by seeding generators. However, these effects are observed only at high concentrations of silver iodide and are not observed consistently.

3.6 EFFECTS OF SILVER ON PLANTS

Silver is a normal constituent of many plants, although the levels are highly variable (Boyle 1968; Smith and Carson 1977). The silver concentration often varies with the season, plant species, silver species, and the ability of the plant to accumulate silver. This makes the establishment of baseline values for silver concentration difficult (Klein 1978e). The present knowledge of the effects of silver on plants has been reviewed by Klein (1978e), and Smith and Carson (1977). Most of the effects of silver reported in the literature are based on a readily-soluble form of silver such as silver nitrate and, therefore, cannot be used to predict the impact of silver iodide which is only slightly soluble. Laboratory studies of silver iodide uptake indicate that the silver from silver iodide is taken up to a lesser extent than silver from silver nitrate. Silver iodide caused definite inhibitory effects at high concentrations but either no effect or a stimulatory effect at lower levels (Klein 1978e). Klein concludes that the accumulation of silver iodide in surface soil zones, even at levels much higher than expected from cloud-seeding activities, should cause no discernable effect on plants.

3.7 EFFECTS OF SILVER ON ANIMALS

Silver is found in the tissues of many animals. The silver content of tissue ashes varies from undetectable to 50 ppm in some vital parts, with average levels being 1 to 10 ppm (Smith and Carson 1977). Smith and Carson have tabulated data on the sensitivity of various aquatic and terrestrial animals to the toxic effects of silver. Concentrations as low as 5 ppb of silver ion are toxic to several marine species (*Daphnia*, guppies, sticklebacks). Davies and Goettl (1978) reported that concentrations of 0.2 ppb showed some toxic effects on rainbow trout, and concentrations of 7 ppb were extremely toxic (50% mortality in 96 hours). At sub-lethal concentrations, silver can retard the growth of freshwater fish. The effects of silver are most pronounced in soft water. Silver shows less toxicity in hard alkaline waters of pH 7.5 to 9.5 (Smith and Carson).

Even though silver iodide is relatively insoluble in pure water, enough silver can theoretically dissolve (1.08 ppb Ag at 25°C, 0.45 ppb Ag at 15°C) to pose a potential hazard. Davies and Goettl (1978) conclude, however, that it would be nearly impossible for enough silver iodide to dissociate in a flowing stream environment to provide toxic levels of ionic silver. Studies in an alpine lake situated in a weather modification program area confirmed that silver presented no imminent threat to the marine ecosystem, even after 10 years of weather modification activities.

The literature on effects of silver ion on terrestrial animals has been reviewed by Klein (1978h) and Smith and Carson. Since most of the information concerns silver ion, this information is not directly relevant to weather modification concerns. In general, silver in itself is not harmful, except in extremely high doses, but accentuates the effects of other stress factors such as copper deficiencies (Klein 1978h). Klein concludes that any effects of silver from weather modification studies, if they occur, would be extremely difficult to monitor or confirm because of the low levels of free ionic silver released from silver iodide, and the possibilities of complexation of any released silver with organic and

inorganic materials in the natural environment.

Smith and Carson (1977) have summarized the results of tests of carcinogenic effects of silver. They conclude that silver may act as a non-specific irritant rather than a carcinogen, and, then, only at dosages and contact times that are not environmentally relevant.

3.8 EFFECTS OF SILVER ON HUMANS

Silver is a normal constituent of various human tissues at concentrations of 0.25 ppm to 10 ppm (ash basis), although it has no known function and is, therefore, presumed to be a contaminant (Smith and Carson 1977). The average human intake of silver from food has been estimated at 88 µg/day (Kehoe et al., 1940 cited by Smith and Carson). Although as much as 10% of total ingested silver may be retained in the body, only about 4% is retained in the tissues (Durbin 1960; Furchner et al. 1968, cited by Klein 1978). Smith and Carson (1977) and Klein (1978g) reviewed the current knowledge of the effects of silver on human health. The overall conclusion is that the effects are negligible. Acute toxic effects of silver or silver compounds in humans have resulted only from accidental or suicidal overdoses of medical forms of silver. No systematic pathology has been directly attributed to silver among workers exposed occupationally. The only proven effect of chronic exposure to silver is argyria or argyrosis which is considered a cosmetic and psychological concern rather than a physiological concern (Smith and Carson). Workers in continued contact with silver iodide from seeding generators have reported problems of skin staining but no toxic effects (Klein 1978h).

Detailed studies of the potential carcinogenity of silver emphasize the improbability of silver causing harmful effects in humans (Fujita 1972, cited by Klein 1978h). Smith and Carson conclude that the magnitude of the threshold limit value ($0.01\ mg\ m^{-3}$) and the US Public Health Service drinking-water standards for silver (50 ppb) misrepresent the relative danger from silver compared with known toxic materials.

4. SILVER IN THE ENVIRONMENT: A PERSPECTIVE

4.1 INTRODUCTION

Since the beginning of extensive weather modification programs, various groups have expressed concern about the possible toxic effects of silver iodide ice-nucleating agents, citing the known toxic effects of ionic silver. Most of these groups are unaware of the ubiquity of silver in the environment and the extensive releases from industrial sources.

4.2 SILVER CONCENTRATIONS IN SOME COMMON MATERIALS

Silver is present in small quantities in coals, petroleum products, fertilizers, and cements. Boyle (1968) reports silver concentrations in coal ashes from Canadian coals ranging from 0.5 ppm to 300 ppm, with most coal ashes containing less than 10 ppm. Smith and Carson (1977) tabulate the silver concentrations in various US coals. Western coals commonly contain 1 to 10 ppm silver in the coal ash. Petroleum products also contain silver at trace levels (Boyle 1968; Smith and Carson 1977), with typical concentrations of 70 to 200 ppb in gasoline, 0.1 ppb in fuel oil, and 0.1 to 1.3 ppm in used diesel oil. Three Alberta gasolines tested by ARC showed silver concentrations of 1 to 2 ppb. The silver in petroleum products is found predominantly in the light and medium paraffinic fractions (Boyle 1968). Silver in fertilizers is usually present at less than 5 ppm except for some phosphate-based fertilizers which contain concentrations of 10 to 1000 ppm, with an average of 15 to 20 ppm (Smith and Carson). Many of the products used in the cement manufacturing industry contain trace levels of silver ranging from 0.07 ppm to 0.7 ppm.

Table 7 shows the industrial uses of silver in the United States. Although the most common dental alloys contain 67% to 70% silver, the human uptake from this source is considered insignificant (Smith and Carson). Several of the important industrial uses of silver (photographic materials, mirrors, batteries, contacts and conductors, and catalysts) result in products that release silver to

Table 7. Industrial use of silver in the United States, 1972.[a]

	%	
Electroplated ware	8.5	
Sterling ware	18.0	
Jewelry	3.23	
Photographic materials	25.3	
Dental and medical supplies	1.33	
Mirrors	0.81	
Brazing alloys and solders	8.09	
Batteries	3.99	
Contacts and conductors	24.1	
Catalysts	2.27	
Bearings	0.23	
Miscellaneous	4.22	
Total	100.02%	4698 Tonnes

[a] Adapted from Smith and Carson (1977).

the environment during disposal. Canadian statistics for 1949 to 1961 indicate that the average industrial consumption of silver in Canada was about 150 tonnes and the average total consumption about 300 tonnes (Patterson 1963). The largest use of silver during this period was for coinage. In 1961, photographic uses accounted for 36% of the industrial silver consumption; silverware, 31%; brazing alloys, 5%; and miscellaneous uses, 28%. This pattern has undoubtedly changed with the substitution of nickel in coinage, stainless steel in tableware, and increased industrial usage.

4.3 SILVER LOSSES TO THE ENVIRONMENT

Smith and Carson (1977) reviewed the information on losses of silver to the environment. They conclude that more silver may be lost from inadvertent sources such as iron and steel production, cement manufacture, and fossil fuel combustion than is lost from the mining, milling, and fabrication of silver materials, at least with respect to atmospheric emissions. The chief losses of silver to the environment occur during use and disposal of various industrial materials, especially photographic wastes.

The losses from mining and milling wastes can be significant. Although Alberta has no silver mining operations (Boyle 1968; Patterson 1963) extensive silver mining operations are conducted in southeastern British Columbia, northern Idaho, and central and western Montana. Any atmospheric emissions from these sources could affect ambient silver concentrations in Alberta. The losses of silver from copper and nickel smelting and refining can also be large. This is a potential silver emission source in Alberta (Sherritt-Gordon, Fort Saskatchewan). Smith and Carson quote Environment Protection Agency estimates of 7 kg of silver per day emitted from a single copper smelter in central Montana.

The total environmental losses of silver from use and disposal are large but only about 5% is lost to the atmosphere (Smith and Carson). The most significant losses occur during silver recovery from photographic wastes and incineration of urban refuse. Smith and Carson attempted to estimate the losses of silver to the

environment from cloud-seeding practices. In the United States, the cloud-seeding loss represented about 1% of the total silver loss to the atmosphere and less than 0.2% of the total loss of silver to the environment. Smith and Carson quote one US survey of silver emissions (GCA Corporation 1973) as stating that the largest emitters of silver to the atmosphere were not related to the silver industry but were inadvertent sources. Table 8 summarizes the estimated losses of silver to the environment. While this data is not directly applicable to Alberta, or Canada, it does give some estimate of the potential importance of various sources.

GCA Corporation estimated that iron and steel-making operations, cement manufacture, and burning of fossil fuels were the major sources of silver emissions. Smith and Carson questioned the losses attributed to iron and steel-making operations, and the cement industry, stating that insufficient information was available to verify these estimates. However, they agreed with the emissions estimated for fossil fuel combustion, citing other calculations that arrive at similar estimates.

4.4 CONCLUSIONS

Much of the information available in the literature is probably not relevant in estimating silver losses to the environment in Alberta. Silver mining and milling operations are non-existent in Alberta; however, ambient silver concentrations could be affected by emissions in neighboring areas. A possible source of silver from copper and nickel refining operations is the Sherritt-Gordon plant in Fort Saskatchewan. The combustion of fossil fuels, cement manufacture, and disposal of urban refuse and photographic wastes could possibly be significant sources of silver emissions in Alberta. The importance of these potential sources relative to cloud-seeding operations cannot be assessed with the presently available information.

Table 8. Annual losses of silver to the environment in the United States (tonnes).[a]

Loss Category	Air	Water	Total Environment[b]
Mining and Milling	1.3	21.8	96.4
Smelting and Refining	39 to 60(?)[c]		290 to 500(?)
Fabrication	3.0	15.5	5 to 8
Use and Disposal Total	28.6	124	1216
Photography	2.2	4.0	
Urban Refuse	21.1		
Cloud Seeding	3.1		
Inadvertent Sources Total	220(?)		850(?)
Steelmaking	31 to 47(?)		
Iron Foundries	12(?)		
Cement Manufacture	96(?)		
Fossil Fuels			
Petroleum Based	15.6		
Coal	38.6		
Total	300		2425 to 2612

[a] Adapted from Smith and Carson 1977.

[b] Includes land, air, and water.

[c] (?) Indicates uncertain estimates.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Much of the information on the toxicological effects of silver has been obtained using silver ion. The results are, therefore, not directly relevant to the assessment of effects from silver iodide cloud-seeding agents. Although silver ion causes toxic effects in many organisms, the amount of free ionic silver present in the environment is probably extremely low because of adsorption or complexation with organic and inorganic materials in the environment. Significant dissociation of silver iodide to ionic silver in the environment is unlikely. The relative importance of silver emissions from cloud-seeding activity and other sources in Alberta in unknown. The general conclusion by all reviewers (Smith and Carson 1977; Klein 1978; Howell 1977; Cooper and Jolly 1969, 1970) is that the potential environmental effects of silver-based nucleating agents are negligible and become insignificant when compared to other sources of silver in the environment.

5.2 RECOMMENDATIONS

1. If an accurate assessment of the impact of silver from cloud-seeding activities in Alberta is required, an effort should be made to determine the sources of silver emissions in Alberta and the natural or background concentrations in the environment.
2. Although the current consensus is that silver iodide has negligible impact on the environment, the research literature should be monitored by those engaged in cloud-seeding activities to confirm if this conclusion remains valid.

6. REFERENCES CITED

Boyle, R.W. 1968. Geochemistry of silver and its deposits. Geological Survey of Canada, Bulletin 160. 264 pp.

Cameron, D.R. 1973. Modelling silver transport in the soil. Fort Collins, COL: Colorado State University. 116 pp. Ph.D. Thesis. (Cited by Klein 1978d).

Cooper, C.F. and W.C. Jolly. 1969. Ecological effects of weather modification: a problem analysis. University of Michigan, Ann Arbor, Michigan. 160 pp.

Cooper, C.F. and W.C. Jolly. 1970. Ecological effects of si ver iodide and other weather modification agents: a review. Water Resources Research 6(1):88-98.

Davies, P.H. and J.P. Goettl, Jr. 1978. Evaluation of the potential impacts of silver and/or silver iodide on rainbow trout in laboratory and high mountain lake environments. (In Klein 1978a, 149-162).

Dessens, J. 1980. Experience francaise de prevention de la grele par generateur au sol: essais d'un nouveau type de controle. Third WMO Scientific Conference on Weather Modification Proceedings. Geneva, Switzerland: World Meterological Association; 2:591-597.

Dessens, J. 1979. Ground seeding hail prevention experiment in France. J. Weather Modif. 11:4-17.

Douglas, W.J. 1968. Toxic properties of materials used in weather modification. Proceedings of the First National Conference on Weather Modification, Boston, Mass: American Meterological Society. (Cited by Smith and Carson 1977.) pp. 351-360.

Durbin, P.W. 1960. Metabolic characteristics within a chemical family. Health Physics 2:225-238. (Cited by Klein 1978g.)

Fujita, S. 1971. Silver palladium-gold alloys carcinoyenity and acid mucopolysaccarides in the induced tumors. Shika Igaku 34(6):918-932. (Chemical Abstracts 77:136 075a.) (Cited by Klein 1978g.)

Furchner, J.E., C.R. Richmond, and G.A. Drake. 1968. Comparative metabolism of radionuclides in mammals. IV. Retention of silver-110 in the mouse, rat, monkey and dog. Health Physics 15(6):505-514. (Cited by Klein 1978g.)

GCA Corporation. 1963. National Emissions Inventory of Sources and Emissions of Silver. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. (Cited by Smith and Carson 1977.)

Guidelines for Canadian drinking water quality. 1978. Hull, Quebec. Health and Welfare Canada. 76 pp.

Howell, W.E. 1977. An overview of he skywater IX conference on precipitation management and the environment. Presented to the Weather Modification Association. Salt Lake City, Utah; April 1977. 29 pp.

Jenne, E.A., D.C. Girvin, J.W. Ball, and J.M. Burchard. 1978. Inorganic speciation of silver in natural waters-fresh to marine. (In Klein 1978a, pp. 41-62.)

Kehoe, R.A., J. Cholka, and R.V. Story. 1940. A spectro-chemical study of the normal ranges of concentration of certain trace metals in biological materials. Journal of Nutrition 19:579-592. (Cited by Smith and Carson 1977.)

Klein, D.A., Editor. 1978a. Environmental impacts of artificial ice nucleating agents. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, Inc. 260 pp.

Klein, D.A. 1978b. Biochemical effects of silver. (In Klein 1978a, pp. 63-72.)

Klein, D.A. 1978c. Effects of microorganisms. (In Klein 1978a, pp. 73-92.)

Klein, D.A. 1978d. Soil microbiological processes. (In Klein 1978a, pp. 93-108.)

Klein, D.A. 1978e. Plant effects. (In Klein 1978a, pp. 109-126.)

Klein, D.A. 1978f. Potential impacts on aquatic systems. (In Klein 1978a, pp. 127-148.)

Klein, D.A. 1978g. Effects on humans. (In Klein 1978a, pp. 169-176.)

Klein, D.A. 1978h. Silver effects: other terrestrial organisms. (In Klein 1978a, pp. 177-188.)

Lindsay, W.L. and M. Sadiq. 1978. Theoretical solubility relationships of silver in soils. (In Klein 1978a, pp. 25-42.)

Mulvey, G. 1978. Atmospheric transport processes. (In Klein 1978a, pp. 9-24.)

Patterson, J.W. 1963. Silver in Canada. Department of Mines and Technical Surveys. Mineral Resources Division, Mineral Survey 3. Ottawa, Ontario. 110 pp.

Peterson, T.A. 1971. An analysis of thirteen years of commercial hail suppression in Alberta. Edmonton, Alberta: University of Alberta. 179 pp. Ph.D. Thesis.

Shewchuk, S.R. 1979. Potential impact of weather modification activity on Saskatchewan - an environmental silver study. Saskatchewan Research Council Report Number P79-7. Saskatoon, Saskatchewan. 35 pp.

Smith, I.C. and B.L. Carson. 1977. Trace metals in the environment. Volume II: Silver. Ann Arbor, Michigan. Ann Arbor Science Publishers Inc. 492 pp.

Sokol, R.A. and D.A. Klein. 1975. The response of soils and soil microorganisms to silver iodide weather modification agents. Journal of Environmental Quality 4:211-214. (Cited by Klein 1978d.)

Teller, H.L., D.R. Cameron, and D.A. Klein. 1976. Deposition of silver iodide used as a seeding agent in ecological impacts of snowpack augmentation in the San Juan Mountains of Colorado, pp. 105-139 of Final report of San Juan Ecology Project. U.S. Department of Commerce, NTIS report No. PB-255-012. Washington. (Cited in Klein 1978a.)

Weaver, T.W., III. 1972. Effects of seeding agents on microorganism and plants. Impacts of induced rainfall on the Great Plains of Montana. Interim Research Report No. 26. Montana Agriculture Experimental Station, Montana State University Bozeman, pp. 34-40. (Cited by Klein 1978d.)

Zacharuk, E., R. Erb, and G.G. Goyer. 1979. Dispersion of silver iodide in cloud seeding experiments. Research, operations and evaluation in the Alberta Hail Project. Volume 2-C: Research-Precipitation Studies. Alberta Research Council, Atmosperic Sciences Department Report 79-1, pp. 64-86.